AD-A104 805 NAVAL RESEARCH LAB WASHINGTON DC F/6 12/1

MODIFICATIONS OF A SHIP TRACKING ALGORITHM FOR MANEUVER FOLLOWI--ETC(U)

OCT 81 W W WILLMAN

UNCLASSIFIED NRL-MR-4579 NL

1 OF 1

AD A
104805

END

DATE
FILMED

10-81

DTIC

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NRL Memorandum Report 4579

2. GOVT ACCESSION NO.: AD-A104 805

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): MODIFICATIONS OF A SHIP TRACKING ALGORITHM FOR MANEUVER FOLLOWING AND BEARING-ONLY DATA

5. TYPE OF REPORT & PERIOD COVERED: Interim report on a continuing NRL problem.

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): W. W. Willman

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, DC 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: SSPO 11224N; J0092-SB; 79-1433-0-1

11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Sea Systems Command, Washington, DC 20362

12. REPORT DATE: Oct[redacted]981

13. NUMBER OF PAGES: 13

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ship tracking
Command and control
Recursive filtering
Kalman filtering
Ocean surveillance
Adaptive driving noise
Bearing-only tracking

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two modifications are described which have been developed for the single-target ship tracking algorithm of NRL Report 7969 and NRL Memorandum Report 3991. One modification improves the tracking response to strong target maneuvers, and the other allows the use of reports giving target bearing only.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

MODIFICATIONS OF A SHIP TRACKING ALGORITHM FOR

MANEUVER FOLLOWING AND BEARING-ONLY DATA

Background

Some refinements were described in Ref. 1 for the ship tracking algorithm developed in Ref. 2. The availability of these two references is assumed in this report. One of the refinements of Ref. 1 is extended here to provide better responsiveness to strong target maneuvers. Also, another modification is introduced to allow the tracking algorithm to operate on bearing-only reports.

Upon the receipt of each new position report, the tracking algorithm basically operates in planar (x,y) coordinates by first updating an estimate of the ship's motion-state vector $(x,y,\dot{x},\dot{y})$ with a Kalman filter, then updating an estimate of a 2x2 "driving noise" covariance matrix Q with the "innovations" from this filter. This Q matrix estimate is then modified to make it diagonal with respect to the current estimate of the velocity vector.

The main refinement of Ref. 1 was to adjust the velocity components of the "state covariance matrix" at this point whenever the estimate of the driving noise had increased. In the currently estimated "in-track" and "cross-track" coordinates, this adjustment consisted of an increase in the (2x2) velocity covariance submatrix by $(t-t_o)^{-1}\tilde{Q}$, where each component of $\tilde{Q}$ is the greater of zero and the change in the corresponding component of Q from its preceding value, and where t is the current time and t_o is the time that tracking started. This refinement produced dramatic performance improvements in some cases by correcting the original algorithm's tendency to adhere too rigidly to the "average velocity" estimated from early data. The rationale for this particular adjustment of the velocity covariance submatrix was that it is exactly the correction that would be needed in the state covariance matrix after two position reports if this matrix were generated by the Kalman filter using too low a value of the driving noise.

For the third and following position reports, this same rationale is extended here to derive corresponding adjustments of the (2x2) position covariance submatrix and the expected values (Kalman filter estimates) of the position and velocity. These further adjustments do not make the kind of dramatic improvement produced by adjusting the velocity covariance submatrix, but they do cause the algorithm to respond more rapidly and accurately to strong target maneuvers. This reduces the need for adopting ad hoc maneuver detection schemes, which often have unclear effects on the "error ellipses" and location likelihoods that can be generated by this algorithm.

Manuscript submitted August 10, 1981.

Also developed here is an alternate way to updating the estimate of the driving noise matrix with the Kalman filter residuals. This alternative is based on the approximation that the in-track and cross-track components of the driving noise are equal in intensity and independent. This simplification is essential in using bearing-only reports (or position reports with long, narrow "containment ellipses") to estimate the driving noise because the procedure used in Ref. 1 depends heavily on the individual reports localizing the ship in two dimensions. It could probably also be used with well-localized reports without sacrificing very much precision, since the estimated driving noise in such cases is usually fairly isotropic anyway when the procedure of Ref. 1 is used.

Only planar tracking in x,y coordinates is discussed here. Extensions to tracking on a sphere can be made along the lines described in Ref. 1 and 2.

New Method for Altering Posterior State Density Parameters in Response to an Increase A in Estimated Driving Noise Intensity Matrix

In the following, let M denote the posterior state covariance matrix just before the report at time t_i and let P denote this matrix just after the preceding report. Also let M and P be partitioned into 2x2 partitions corresponding to position and velocity variables as

$$M = \left[\begin{array}{c|c} M_1 & M_2 \\ \hline M_2^T & M_3 \end{array}\right] \quad \text{and} \quad P = \left[\begin{array}{c|c} P_1 & P_2 \\ \hline P_2^T & P_3 \end{array}\right]$$

where M_1 is a position covariance matrix, etc. If (and only if) a positive-semidefinite increase A occurs in the processing of the report at time t_i (i.e., after the Kalman filter updating of the posterior state density parameters), these parameters are then further altered in this new method as follows:

1. Velocity Covariance Submatrix K:

For the second and following reports, K is replaced by K + δK, where

$$\boxed{\delta K = \frac{1}{t_i - t_o} \cdot A,}$$

with a certain positive definite upper limit on δK. t_o is the time of the initial report. This adjustment is the refinement of Ref. 1 mentioned earlier, and is described in detail there.

2. Velocity Mean $\hat{V}$ (a 2-vector):

For the third and following reports, it is assumed that P_3 also should have been increased by δK and that the P_2 value is negligible. Hence, for the third and following observations only, $\hat{v}$ is replaced by $\hat{v} + \delta\hat{v}$, where

$$\hat{v} + \delta\hat{v} = \bar{v} + (M_1 + A \frac{\tau}{t_i - t_o})^T (M_1 + A\tau + R)^{-1} (z - \bar{x}),$$

according to the Kalman filter equations, and where $\tau = t_i - t_{i-1}$ and the rest of the notation is as in Refs. 1 and 2. For simplicity and from good numerical experience, the approximation

$$\hat{v} \cong \bar{v} + M_2^T (M_1 + R + A\tau)(z - \bar{x}),$$

is adopted. Hence, the correction for $\hat{v}$ becomes

$$\boxed{\delta\hat{v} = \frac{\tau}{t_i - t_o} A (M_1 + R + A\tau) (z - \bar{x}).}$$

3. Position Covariance Submatrix B:

No good theory is available for adjusting the entire (4x4) state covariance matrix for large A, which is the case of major interest, because of incomplete state observability. Hence, the position-velocity submatrix is not adjusted, and a positive-semidefinite (2x2) increment δB is sought for B, so that the resulting (4x4) state covariance matrix is still positive-definite. Now

$$B = M_1 - M_1(M_1 + R)^{-1}M_1.$$

After an estimated $A > 0$, we only consider one previous report because position is directly observable. Hence, from the Kalman filter propagation equations, the difference δM_1 caused by Q being augmented by A is

$$\delta M_1 = A\tau,$$

so

$$B + \delta B = M_1 + A\tau - (M_1 + A\tau)(M_1 + R + A\tau)^{-1}(M_1 + A\tau).$$

If terms of second order in $A\tau$ are neglected here,

$$\delta B = A\tau + M_1(M_1+R)^{-1}M_1-(M_1+A\tau)[(M_1+R)^{-1}-(M_1+R)^{-1}A\tau(M_1+R)^{-1}](M_1+A\tau)$$

$$= A\tau - A\tau(M_1 + R)^{-1}M_1-M_1(M_1+R)^{-1}A\tau + M_1(M_1+R)^{-1}A\tau(M_1+R)^{-1}M_1$$

$$= [I-M_1(M_1+R)^{-1}]A\tau[I-(M_1+R)^{-1}M_1]$$

$$= R(M_1+R)^{-1}A\tau(M_1+R)^{-1}R$$

Now, for one-dimensional motion,

$$\delta B = \frac{R^2 A\tau}{(M_1 + R)(M_1 + R + A\tau)}$$

exactly for any $A\tau$. Hence, to be conservative and to compensate for the fact that the position-velocity submatrix is not being altered here, we use

$$\boxed{\delta B = R(M_1+R+A\tau)^{-1}A\tau(M_1+R+A\tau)^{-1}R.}$$

This adjustment is also not used until the third report because the relatively large initial speed variance gives good results without it at the second updating time.

4. Position Mean $\hat{x}$: (2-vector)

From the Kalman filter equations for updating with the position report z at time t_i,

$$\hat{x} = \bar{x} + M_1(M_1+R)^{-1}(z-\bar{x})$$

and

$$z - \hat{x} = [I-M_1(M_1+R)^{-1}](z-\bar{x}).$$

As before,

$$\delta M_1 = A\tau$$

is taken after an estimated positive-definite A. Thus $\hat{x}$ is replaced by $\hat{x} + \delta\hat{x}$, with

$$\hat{x} + \delta\hat{x} = \bar{x} + (M_1+A\tau)(M_1+A\tau+R)^{-1}(z-\bar{x}).$$

Now,

$$\begin{aligned}
z-(\hat{x}+\delta\hat{x}) &= [I-(M_1+A\tau)(M_1+A\tau+R)^{-1}](z-\bar{x}) \\
&= R\ (M_1+A\tau+R)^{1}(z-\bar{x}) \\
&= R(M_1+A\tau+R)^{-1}(M_1+A\tau+R-A\tau)(M_1+R)^{-1}(z-\bar{x}) \\
&= R[I-(M_1+A\tau+R)^{-1}A\tau](M_1+R)^{-1}(z-\bar{x}) \\
&= [M_1+R-M_1-R(M_1+A\tau+R)^{-1}A\tau](M_1+R)^{-1}(z-\bar{x}) \\
&= [I-M_1(M_1+R)^{-1}](z-\bar{x})-R(M_1+R+A\tau)A\tau(M_1+R)^{-1}(z-\bar{x}) \\
&= (z-\hat{x})-R(M_1+R+A\tau)A\tau(M_1+R)^{-1}(z-\bar{x}).
\end{aligned}$$

Thus, the adjustment

$$\boxed{\delta\hat{x} = R(M_1+A\tau+R)A\tau(M_1+R)^{-1}(z-\bar{x})}$$

is used, but not until the third report is processed for the same reason as in the case of the position covariance submatrix.

Summary

Only adjustment 1 is made after the second position report (and, of course, only if a positive-definite A is estimated then by the procedure described in Ref. 1); then all of the adjustments 1-4 are used thereafter whenever $A > 0$ is estimated. Making these adjustments only when $A > 0$ is compensated by the fact that corrections are only made one step back for the position-component parameters B and $\hat{x}$ of the posterior probability density function.

An example of the numerical significance of using all four of these corrections, instead of only the first one as was done in Ref. 1, is shown in Figures 1 and 2. The input report data is identical in both cases, and corresponds to a ship making a 135° turn and a speed change at time t_5. To keep

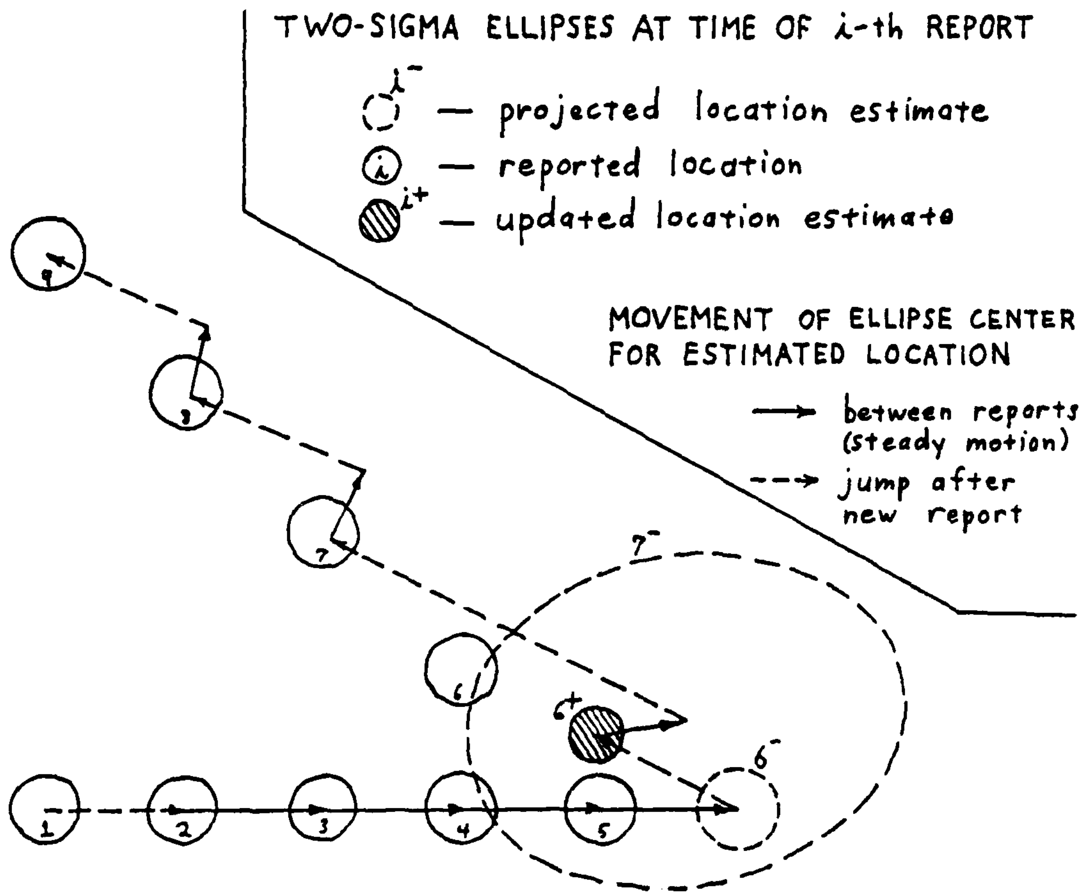


Fig. 1 — Previous method

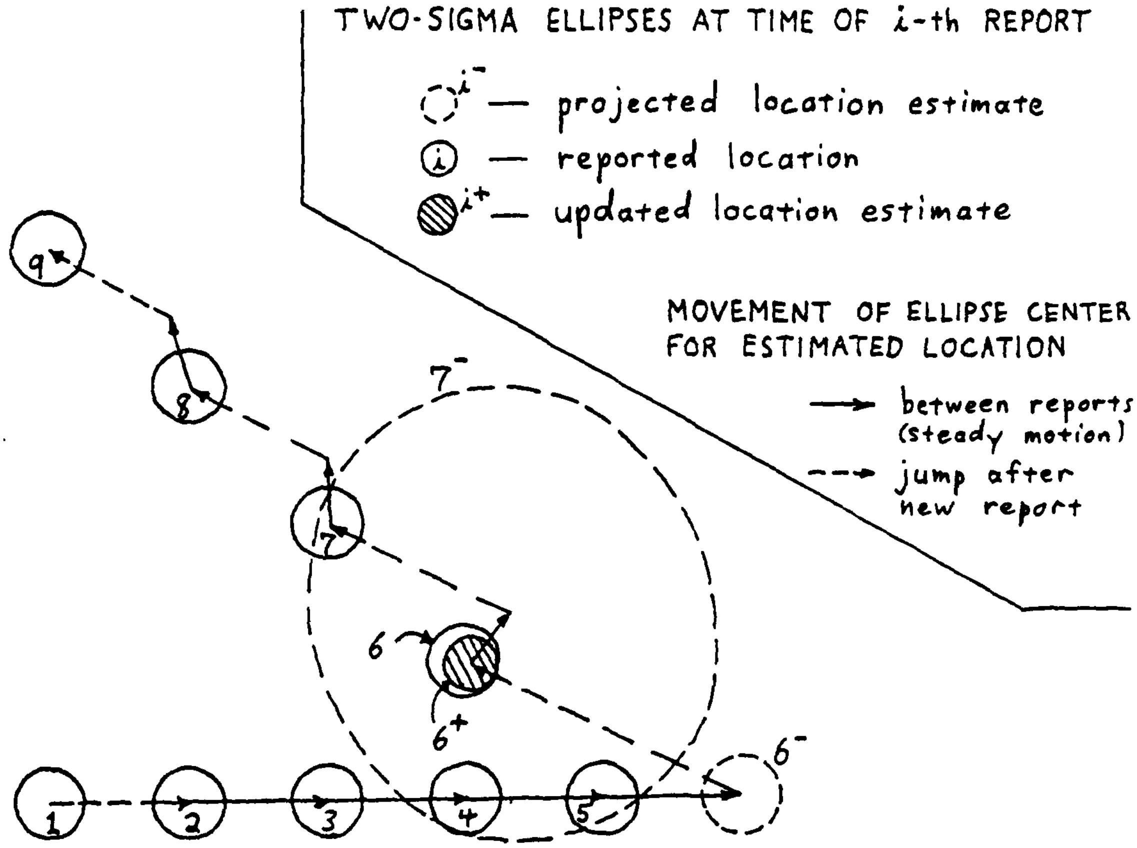


Fig. 2 — New method

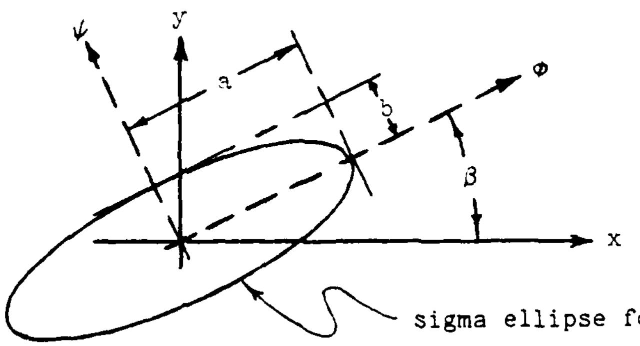
the figures simpler, the two-sigma (90% containment) ellipses for the output location estimates are displayed only for times near this maneuver, which is when they are most different for the two tracking algorithms. The further corrections instituted here do improve the tracking performance following this maneuver, especially in the updated containment ellipse at the sixth observation time and the projected containment ellipse at the seventh observation time. The containment ellipses are also somewhat tighter (but still covering the target) near the end of this track when the new corrections are added, but these are not shown in the figures.

Alternate Method of Estimating Driving Noise Intensity

The basic tracking algorithm here treats ship motion as a steady average-velocity drift superimposed on a two-dimensional Brownian motion due to maneuvering. Both the average velocity (a 2-vector) and the intensity parameter of the Brownian motion (the 2x2 "driving noise intensity" matrix) are estimated from the incoming position-report data. The procedure advocated in Ref. 1 estimates this intensity as if the in-track and cross-track components of the Brownian motion maneuvers were statistically independent. This simplification was adopted because such independence would normally apply to ship motion, and because the report data would not usually support a usefully reliable estimate of anything more refined than this. These two manuevering components were not presumed to be of equal intensity, however, because it was thought that allowing their estimates to be different would often lead to significantly more precise estimates of ship motion; for example, when a ship zigzags about an average course, or when it changes speed a lot but stays on the same heading.

For the case of bearing-only reports, however, the natural extension of this procedure would not give meaningful estimates of the driving noise intensity parameters because of the less direct observability of the motion state. It would probably also perform badly for what is almost the same thing, position reports with long, narrow "error ellipses." The alternate procedure described below can be used in such cases to estimate the driving noise intensity as if the in-track and cross-track components were equal as well as independent.

In the notation of Refs. 1 and 2, the driving noise intensity matrix components q_{xx} and q_{yy} are now presumed equal, and are denoted simply by q here. The q_{xy} component is now zero. Hence, only the single scalar driving noise parameter q is estimated in this alternate method. If the components of the covariance matrix $M_1 + R$ and the orientation of the corresponding sigma-ellipse are as shown below,



sigma ellipse for matrix $(M + R) = \left[\begin{array}{c|c} g_{xx} & g_{xy} \\ \hline g_{xy} & g_{yy} \end{array}\right]$

where M_1 is defined as in the preceding section, then the quantities a^2, b^2, $\sin\beta$ and $\cos\beta$ can be determined as follows:

$$\text{set} \quad a^2 = g_{xx} + g_{yy}$$

$$\text{set} \quad b^2 = \sqrt{(g_{xx} - g_{yy})^2 + 4g_{xy}^{\ 2}}$$

$$\text{set} \quad a^2 = (a^2 + b^2)$$

$$\text{set} \quad \cos\beta = \frac{a^2 + g_{xx}}{\sqrt{(a^2 - g_{xx})^2 + g_{xy}^{\ 2}}}$$

$$\text{set} \quad \sin\beta = \frac{g_{xy}}{\sqrt{(a^2 - g_{xx})^2 + g_{xy}^{\ 2}}} \quad ,$$

where "=" is used in the sense of FORTRAN. Now let

$$\left[\begin{array}{c} \varepsilon_x \\ \hline \varepsilon_y \end{array}\right] = \left[\begin{array}{c} z_x - \bar{x} \\ \hline z_y - \bar{y} \end{array}\right] ,$$

which has zero mean and covariance matrix

$$M_1 + R + Q\tau.$$

The last term in this covariance matrix is due to an independent driving noise increment with covariance matrix

$$\left[\begin{array}{c|c} q\tau & 0 \\ \hline 0 & q\tau \end{array}\right], \text{ so } Q = \left[\begin{array}{c|c} q & 0 \\ \hline 0 & q \end{array}\right].$$

Now let

$$\left[\begin{array}{c} \varepsilon_\phi \\ \hline \varepsilon_\psi \end{array}\right] = \Omega \left[\begin{array}{c} \varepsilon_x \\ \hline \varepsilon_y \end{array}\right], \text{ with } \Omega = \left[\begin{array}{c|c} \cos\beta & \sin\beta \\ \hline -\sin\beta & \cos\beta \end{array}\right].$$

This rotated innovation vector has zero mean and covariance matrix

$$\Omega(M_1 + R)\Omega^T + \Omega Q \Omega^T = \left[\begin{array}{c|c} a^2 & 0 \\ \hline 0 & b^2 \end{array}\right] + \left[\begin{array}{c|c} q & 0 \\ \hline 0 & q \end{array}\right]\tau,$$

since the contribution of the driving noise increment is statistically independent. Hence, if

$$s^2 = \frac{1}{\tau}(\varepsilon_\phi^2 - a^2)$$

and

$$\eta^2 = \frac{1}{\tau}(\varepsilon_\psi^2 - b^2),$$

these two statistics are independent of each other and their counterparts at other report times, and

$$E(s^2) = E(\eta^2) = q.$$

Hence, the alternate procedure advocated here is to use $h = \max(o, \hat{q})$ as a running estimate of q - together with the other parts of the tracking algorithm as before - where $\hat{q}$ is the average of the s^2 and η^2 statistics for all the currently available reports (except that only η^2 is used for the bearing-only reports, and the "e_{max}" limiting procedure of Ref. 1 is used). This average $\hat{q}$ is computed recursively as before. Now there are two recursion updates of $\hat{q}$ at each instance of a position report - one for s_i^2 and one for h_i^2 - but only one for each bearing report. Of course, some modifications in the above procedure for computing η^2 would be needed for the case of a bearing-only report. One could either replace it at the outset with an equivalent position report with a very long variance component along the line-of-bearing

(and then not use the computed s^2 statistic, of course), or one could compute ε_ψ as the cross-bearing component of the observed minus predicted position (as evaluated from the observed bearing at the predicted ship range) and b^2 as the cross-bearing component of M_1 plus $r^2\sigma^2$, where r is the predicted range and σ^2 is the bearing variance. With either procedure, a reasonable value of the statistic η^2 could then be computed.

References

1. W. W. Willman, "Some Refinements for a Ship Tracking Algorithm," NRL Memorandum Report 3991, May 2, 1979.

2. W. W. Willman, "Recursive Filtering Algorithms for Ship Tracking," NRL Report 7969, April 6, 1976.